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SOME OBSERVATIONS ON DEW

By I. F. LONG

General.—Dew may be defined as "the deposition of water drops by direct condensation of water vapour from the adjacent clear air", in general upon surfaces cooled by nocturnal radiation. In this definition the phrases "direct condensation" and "clear air" should be firmly adhered to. Deposition, or the appearance of water by other agencies should if possible be clearly indicated by observers in their records and if possible the source of the water noted, but these phenomena should not be recorded as dew. For example; large amounts of water are often deposited on plant and soil surfaces during overcast nights when a warm saturated air mass suddenly replaces a cool dry air mass, giving rise to mist and fog. The deposition in such cases is usually in the form of fog precipitation, the droplets formed becoming quite large especially upon grass and other non-wettable surfaces. These droplets coalesce and stream down the blades to wet the lower regions of the plant and the soil, a condition rarely found in true dew deposition. Plate I (between pp. 176–177) shows this form of fog precipitation upon short grass about 1½ inches high. Note the large amount of water and the general over-all covering of the droplets. Bare soil also becomes thoroughly wetted on such occasions whereas it is, relatively speaking, quite dry on nights of true dew deposition.

Another form of water on plant leaves, particularly on grass, which may be mistaken for dew, is the water exuded by the plants themselves and known as guttation[1]. Guttation will quite often occur on overcast nights when the soil is warm and at or near field capacity. The next morning the grass is covered with large glistening "dew drops" and many observers mistake these exuded drops for dew, but this is a physiological and not a meteorological phenomenon.

Dew and guttation often occur together and careful observation is needed to distinguish between the dew and guttation droplets. The water of guttation is exuded only at the tips of the blades in large drops which are generally about 2 millimetres in diameter and sometimes reach 3 millimetres diameter before trickling down the leaf surface. The dew droplets on the other hand rarely grow greater than 1 millimetre diameter, are spread fairly evenly over the leaf

surface, are usually larger at the edges of the leaves than at the centre, and become smaller and smaller trailing off to nothing in the lower warmer depths of the plant. Plate II shows dew and guttation occurring together, and Plate III guttation alone.

Measuring dew.—Many instruments have been devised for the observation and measurement of dew, some by observation of the deposition of droplets upon a standard surface[2] and others by directly weighing an object or plant upon which dew is forming; each have their own advantages and disadvantages. Hirst[3] has devised a "dew balance" which weighs and records the deposition on a plant shoot, and Jennings and Monteith[4] a "dew balance" which weighs and records the deposition on a growing plant in soil. Hirst's balance weighs the total deposition of dew, and gives a good picture of the rate of dew formation, but it does not distinguish between dew deposited from vapour "rising" from the soil or from vapour "falling" from the air above the crop. The Jennings and Monteith balance, on the other hand, measures the total gain or loss of the plant–soil–water system as a whole, but does not measure the actual deposition of dew. It would seem that a combination of the two types of balance is desirable. A simple approximate method of measuring dew is to weigh the amount of water absorbed by pieces of filter paper of known area and weight, which have been carefully and firmly pressed on to a grass surface[5]. When guttation occurs with the dew this method measures the total surface water.

Source of dew.—The 2,000 year old argument as to whether dew "rises" or "falls" was re-vitalized when Wells wrote his famous "Essay on Dew" in 1812 (see Monteith[5] for brief historical review). Nearly all the arguments have been based upon observations or experiments on grassland, and the tendency has been to apply the conclusions reached to dew in general. One obvious experimental approach is to make a detailed examination of the temperature, vapour pressure and wind gradients above and inside various crops in the field, and of the temperature gradients and moisture content of the soil. To this end apparatus was set up in various crops at Rothamsted during the years 1950–1956. The apparatus consisted of miniature, non-ventilated, nickel resistance thermometers, mounted in pairs with one bulb dry and the other wet, resulting in a compact psychrometer. These units were mounted on light masts in and above the crops from the end of May to the middle of October. Soil temperatures were measured using nickel resistance thermometers and on some occasions leaf temperatures were measured using miniature resistance thermometers which were inserted in the leaves. Continuous recording was obtained using standard 12 point resistance recorders of the double-slidewire type. Wind gradients were recorded using modified sensitive cup anemometers and occasionally a "hot-wire" anemometer was used for spot readings. These instruments enable the onset and finish of dew to be determined to within 5 minutes, and an approximation of the dew intensity can be estimated. Checks against records from a dew balance[3] installed in a potato crop have been good. (For a full description of these instruments see, Penman and Long[6] and Long[7].) The crops examined were grass, potatoes, sugar-beet, Brussels sprouts and spring wheat.

The records obtained in these crops clearly confirm that for moisture to condense on a dry surface, the surface must be at a lower temperature than the dew-point of the air, but for a surface already wetted, the surface temperature need

only be at the dew-point temperature. On clear nights the measured leaf temperatures of potatoes are usually 0·5 to 1·0°C. less than the air a few millimetres from their surface, and on occasions may be 2°C. less. The old idea that leaf temperature rises to the dew-point temperature of the surrounding air when condensation occurs is not supported by the records.

The available records also suggest that dew does not form unless an inversion of the vapour pressure gradient has occurred above the surface of the crops (but see Monteith[5]). When there is no inversion the vapour is transported up the normal gradient from the soil escaping into the upper air and no dew is deposited. Increased air movement in the crop generally results in a greater deposition of dew but only to the point where the increased turbulence does not decrease the slope of the vapour pressure gradient. When this happens, deposition becomes less as the air speed increases.

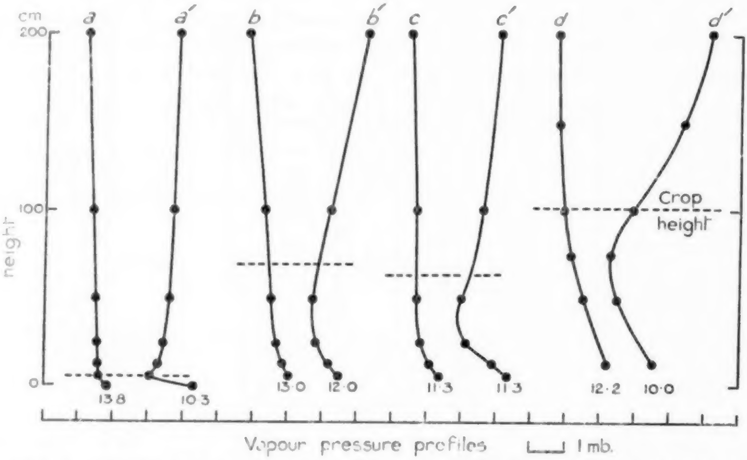

FIGURE 1—NOCTURNAL VAPOUR PRESSURE GRADIENTS IN AND ABOVE (*a*) GRASS, (*b*) BRUSSELS SPROUTS, (*c*) POTATOES, (*d*) SPRING WHEAT.

(*a, b, c, d,*) No dew. (*a′, b′, c′, d′*) Dew. Relative humidity at or near saturation.

Typical vapour pressure gradients during nights of dew formation, and nights with no dew formation are shown in Figure 1 for four different crops. In all four it can be seen that there is an upward decrease of vapour pressure within the crops, indicating that vapour is escaping from the soil continuously, whether or not dew is being deposited. The vapour pressure inversion during dew formation on grass (Figure 1 (*a′*)) occurs almost at the crop surface and sometimes just above, suggesting that much of the water deposited on grass could be obtained by upward transfer from the soil. This shape of vapour profile is typical of grass even when the soil is dry. In the taller crops however the down-coming gradient extends well into the crop. Maximum deposition in these crops is always in the upper two thirds of the crop, and the vapour pressure gradients indicate that in these cases much of the vapour must be

transferred to the crop from the air above. Figure 1 is typical of gradients obtained when the soil is at or near field capacity. When the soil is very dry, the level of the vapour pressure inversion is much lower. The planting density will affect the gradients in and above the crop. For a dense stand with a nearly closed leaf canopy the effective radiating surface is near the top of the crop, so that on clear nights the cooling is more intense at canopy level than in a thin crop where the cooling is most intense at or near ground level. The dense crop also suppresses mixing and transfer processes within it. Both effects combine to move the level of zero vapour pressure gradient nearer to the top of the denser crop and to reduce dew deposition within the denser crop. To illustrate the effects of crop density upon the micro-climate in spring wheat, three plots, ten yards square, were planted or thinned to give densities 200 per cent, 100 per cent and 25 per cent of a normal crop, and the recording psychrometers were installed in and above them.

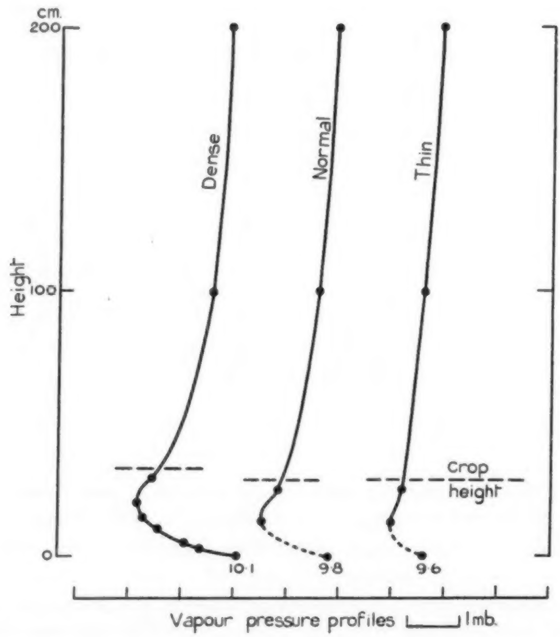

FIGURE 2—EFFECT OF CROP DENSITY UPON VAPOUR PRESSURE GRADIENT DURING DEW FORMATION.

Relative humidity at all levels is 100 per cent.

The three gradients of Figure 2 were obtained during a night of dew and are the average gradients over the period 0300–0400 G.M.T., 5 June 1956. Unfortunately there were only enough psychrometers to record detail in the dense crop, but the few points recorded in the less dense crops clearly indicate the decrease in the gradients above and below the crops, and also the lower height

of the inversion point. The portions of the vapour pressure profiles in the less dense crops where no records were available have been approximated and plotted as a dotted line.

Does dew "rise" or "fall"? It would seem from the preceding observations that it does both, the amounts contributed from the two sources depending upon the relative position of the receiving surfaces to the level of the vapour pressure inversion, as well as the surface temperature and the ventilation.

Routine observations of dew.—The routine recording of dew by agricultural meteorological stations was recommended by the International Meteorological Organization in 1947 (resolution 7 of the Conference of Directors, Washington 1947) and has in fact been recorded by some of the stations under the Meteorological Office Agricultural Scheme in this country since 1924.

At many stations this observation is at 0900 G.M.T. only, and since any dew which may have occurred during the previous night may have evaporated by 0900, it is reasonable to assume that the advent of dew occasionally goes unobserved. The nine o'clock record is more truly an observation of the persistence of dew until 0900. To check this point a comparison has been made between dew occurrence as estimated from the continuous records of vapour pressure, humidity and wind gradients, with the routine meteorological observations taken at this station (Rothamsted) during the months of July and August 1956.

Analysis of the records shows that during this period, dew occurred on 31 occasions. The routine observations show 18 reports of dew for this period of which two reports were actually "guttation" and not dew.

TABLE I—ANALYSIS OF DEW RECORDS FOR AUGUST 1956

	Dew			Gradients and evaporation 0600–0900 G.M.T.		
Date	Intensity	Duration	Finished	(e_1-e_2)	(u_2-u_1)	$E\times 10^{-5}$
		hr.	G.M.T.	mb.	cm. sec.$^{-1}$	gm. cm.$^{-2}$ sec.$^{-1}$
(a) 8	M	7·5	0500	0·13	59	0·15
9	L	4·0	0430	0·03	36	0·02
12	VL	1·5	0330	0·05	66	0·07
22	H	9·5	0630	0·20	39	0·16
23	M	10·5	0515	0·15	25	0·08
29	L	7·0	0545	0·13	28	0·07
30	M	7·5	0545	0·13	38	0·10
(b) 1	L	2·25	0430	0·22	54	0·24
5	M	10·0	0515	0·17	33	0·11
7	L	8·5	0230	0·16	43	0·14
20	M	8·0	0530	0·12	82	0·20
21	H	10·0	0545	0·23	36	0·17
24	L	1·75	0530	0·13	62	0·16
27	M	9·0	0430	0·23	49	0·22

(*a*) Dates when dew occurred and was observed at 0900. (*b*) Dates when dew occurred and was not observed at 0900 G.M.T., possibly because of evaporation.

Dew occurred but was not observed, because of following rain on the 6th, 11th and 25th. Guttation was observed but recorded as dew on the 14th. The intensity of the dew is referred to in the table as follows: H–heavy, M–moderate, L–light, VL–very light.

Some of the August data are in Table I and Figure 3. There were 17 nights on which physical conditions were suitable for dew formation but only on 7 was "dew" reported at 0900 next morning. Three of the missing 10 are accounted

for by rain falling an hour or two after the dew formation had come to an end (6, 11 and 25 August). Table I thus carries information about 7 occasions when dew was observed (*a*) and 7 occasions when it was not observed (*b*). Four occasions from each group are represented in Figure 3 which shows the vapour pressure profiles in a potato crop at the time of steepest gradients. There is no major difference between the groups and the explanation for non-observance of dew in group (*b*) must be found in persistence. Since it is possible that the condensed water may have evaporated by 0900 on mornings when dew was not observed, it was decided to estimate roughly the average rates of evaporation for the periods from sunrise (about 0600) to 0900 following each occurrence of dew. Rider's[8] equation for evaporation has been used, fully realizing that it is being applied under conditions of stability and fetch, and over a time interval

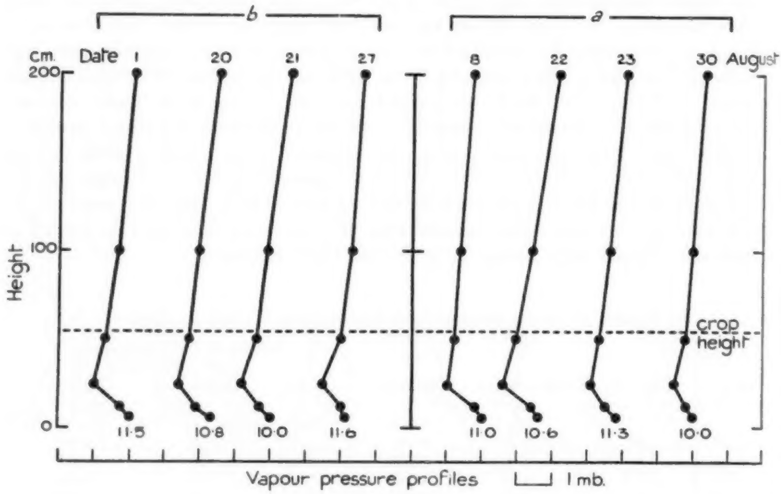

FIGURE 3—COMPARISON OF VAPOUR PRESSURE GRADIENTS FOR SOME OCCASIONS WHEN DEW WAS OBSERVED (*a*) AND WAS NOT OBSERVED (*b*).

Relative humidity at all levels is 100 per cent.

for which it was not designed. The plane of "zero displacement" has been taken as the level of zero vapour pressure gradient (for which there is some justification, not yet published) and in this potato crop the value was $d = 30$ cm. With observation levels at $z_1 = 100$ and $z_2 = 200$ cm., the Rider equation reduces to:

$$E \simeq 2\,(e_1 - e_2)\,(u_2 - u_1)\,10^{-7}\ \text{gm. cm.}^{-2}\ \text{sec.}^{-1}$$

The last three columns of Table I give the vapour pressure and wind velocity gradients per metre, and the derived estimate of evaporation rates. On the mornings of the 22nd and 23rd the period estimated starts on the cessation of dew, at 0630 and 0615 respectively. In comparing the evaporation estimates with dew intensities, two facts should be kept in mind:

(i) A moderate dew in southern England will deposit about 0·1 mm. of water. (A heavy dew may deposit 0·15 mm. or more.)

(ii) An evaporation rate of $0 \cdot 1 \times 10^{-5}$ gm. cm.$^{-2}$ sec.$^{-1}$ over a period of three hours is approximately 0·1 mm. of water.

It can be seen from the table that for all occasions where dew was not observed at 0900 this rate of evaporation was exceeded, and on five of the seven occasions when dew was observed at 0900 this rate of evaporation was not exceeded. Of the two exceptions, the 8th and 22nd, the latter was a night of very heavy dew, and on both nights guttation may have added to the accumulated surface water enough to permit persistence through a period of relatively high evaporation rate.

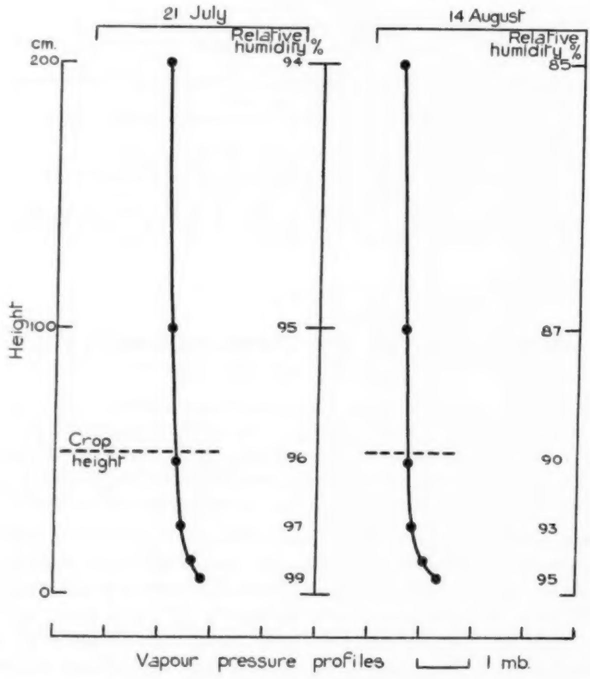

FIGURE 4—VAPOUR PRESSURE GRADIENTS FOR THE TWO OCCASIONS WHEN GUTTATION OCCURRED AND WAS REPORTED AS DEW.

On two mornings during July and August (21 July and 14 August) this guttation was observed but was mistaken by the observer as dew. To justify this verdict, Figure 4 shows the vapour pressure profiles for the previous nights at the times when they came nearest to favouring condensation: the relative humidity at the six heights of observation is also indicated. On both nights the wind at 2 metres was over 2·4 metres per second, and under these conditions it is fair to say that dew formation would not be possible.

Comment.—These notes have been written in an attempt to show that although the nine o'clock observations of dew are useful, the recording of dew is still not all that it might be. Dew can be an important factor in agriculture, for it is known to influence the development of certain plant diseases. Plant pathologists who rely upon routine records for their information on the advent of dew, may be getting misleading underestimates of the frequency of occurrence. Although only two month's records have been considered in these notes, a rough analysis of the records for the two summers 1955–1956 show that dew nights were twice as numerous as occasions when dew was recorded at 0900.

Acknowledgment.—The author wishes to thank Dr. H. L. Penman for guidance and advice during the course of this work.

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MOUNTAIN WAVES OVER SOUTHERN NORWAY, JULY 26, 1956

By Y. GOTAAS, *cand. real*

On July 26, 1956 mountain waves over southern Norway were investigated by means of a jet fighter aircraft (Sabre). The flight was carried out to see if it is possible to reveal main features of mountain wave patterns by the use of high-speed jet aircraft. The aircraft was flying constant attitude at about 25,000 feet and only one run was made. The flight was made between 1100 and 1200 G.M.T.

Synoptic situation, July 26.—The whole day a strong westerly current persisted over southern Norway at all levels. A cold occlusion moved eastwards and passed Gardermoen at 1400 G.M.T. The cloud cover over eastern and central parts of Norway was mainly broken to scattered. The air, being conditionally unstable, contained cumulonimbus clouds with rain showers all along the western coast and in the western mountains. The tops of the cumulonimbus clouds were less than 20,000 feet along the track.

Fig. 1 shows the 300-millibar chart at 1500 G.M.T. and the track of the plane. The flight was made at 7,600 metres, corresponding to the height of the 380-millibar level.

Fig. 2 shows the variation of temperature and wind with height as indicated by the radio-sonde ascent made at Sola Airport at 1500 G.M.T. The cold front is marked by a shallow inversion at about 5,000 metres. The flight was therefore made in the air above the cold front.

Observational flight data.—At the desired height of 25,000 feet the pilot trimmed the plane for straight and level flight and engaged the automatic

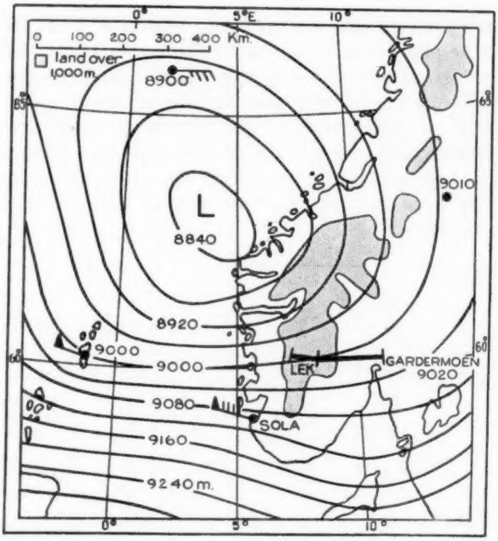

FIG. 1.—300-MILLIBAR CHART, JULY 26, 1956, 1500 G.M.T.
The broad line represents the track of the aircraft. LEK is the radio beacon (at Kalhovd).

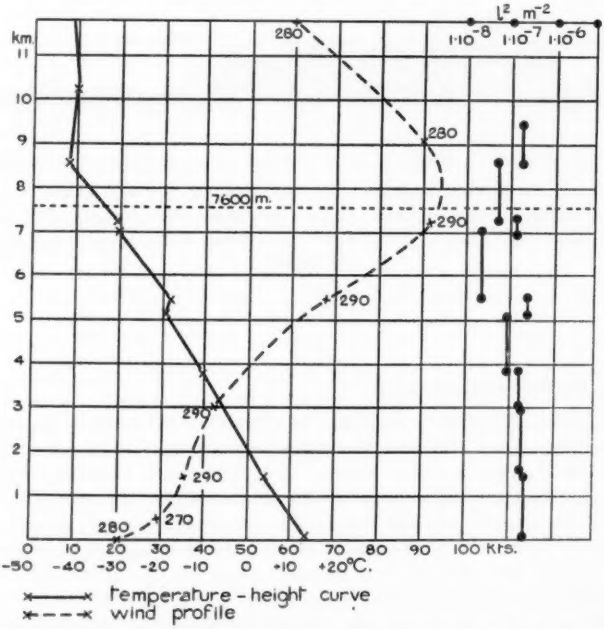

FIG. 2.—TEMPERATURE AND WIND PROFILE AS SHOWN BY THE RADIO-SONDE ASCENT AT SOLA, JULY 26, 1956, 1500 G.M.T.
Wind directions are indicated by figures along wind profile. l^2 is Scorer's parameter.

pilot. The course selected was via the radio beacon at LEK to the beacon at Gardermoen. The pilot started the run 60 kilometres west of LEK and had to alter course 10 degrees when passing this beacon. None of the controls were moved during the run, minor adjustments of the automatic pilot being made to keep the indicated airspeed constant. The vertical speed indicator was used to determine the wave crests and troughs and the altimeter was read at the same time. The maximum and minimum values shown by the vertical speed indicator in between were also noted. The path of the aircraft in the vertical plane is shown on Fig. 3.

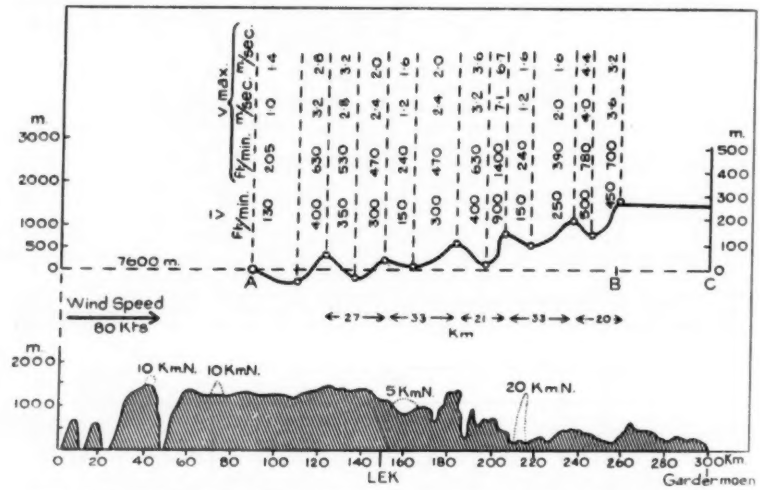

FIG. 3.—MOUNTAIN PROFILE ALONG TRACK PLUS OR MINUS 5 KILOMETRES

Mountain peaks further away are indicated by dotted lines.

Right-hand scale: height in metres for the curve representing the path of the aircraft.

Upper left-hand scale: height in metres if the curve is regarded as representing movements of air particles.

$\bar{v}$ = mean vertical speed. $v_{max} = \frac{\bar{v}\pi}{2}$ (see text).

Notes on the method used.—

(i) Determination of positions: at a height of the order of 25,000 feet the passage over a radio beacon cannot be accurately fixed. An uncertainty of around ½ minute may occur. Pin-points made visually will be helpful for checking purposes when clouds do not cover the ground. Radar, if available, should naturally be used together with the other methods. Time must be read with an accuracy of 10 seconds to obtain an accuracy of 2 kilometres in position at a ground speed of 450 knots. On Fig. 3 the accuracy is of the order of 4 kilometres.

(ii) It is difficult to trim the aircraft for level flight at the start of a run as the aircraft at that time may be situated in a main updraft or downdraft. The resultant mean ascent or descent of the plane, when within

reasonable limits, can easily be calculated and should not seriously affect the result.

(iii) The vertical speed indicator has a lag of around 10 seconds. Readings will therefore be slightly out of phase with the vertical movements of the aircraft and the oscillations damped. Besides, the maximum and minimum values obtained will be smaller than the vertical velocities of the aircraft. It seems better to read off the altimeter every ½ minute and to note its extreme values in between. The pilot can then concentrate on the airspeed indicator and the altimeter only.

(iv) During the flight a certain amount of fuel is consumed. The total weight of the aircraft decreases and when the indicated airspeed is kept constant, this should result in a gradually increasing ascent of the aircraft. This effect, however, seems to be quite small, the ratio of the amount of fuel consumed to the total weight of the aircraft being of the order of a few per cent.

(v) On October 8 the same pilot, flying at 25,000 feet, kept the altitude within 20 feet for a period of 10 minutes, at a run when no waves were encountered. It will therefore be safe to assume that an aircraft can maintain its attitude for a long period, and further that the effect of fuel consumption and of "drift" of the altimeter due to elastic properties can be neglected. The latter condition assumes the pilot does not trim his aircraft for level flight immediately after a quick ascent to the desired altitude. It seems that normal corrections of altimeter readings due to deviations from the International Civil Aviation Organization standards and to changes in surface pressures are sufficient.

Discussion of data obtained.—Fig. 3 is a vertical cross-section showing the mountain profile along the track and the path of the aircraft.

Assume that the waves are stationary. Let $Z(x)$ denote the height of a streamline, and U the wind speed. The vertical velocity of the air particles is then $U(dZ/dx)$. On the other hand, if $Z_a(x)$ denotes the height of the aircraft and V the ground speed, then $V(dZ_a/dx)$ is the vertical velocity of the aircraft. Equating the two velocities, and assuming U and V to be constants, one finds:

$$Z(x) = (V/U)Z_a(x).$$

In the case considered, the ratio V/U is $5{\cdot}5$.

Let $\bar{v}$ denote the mean vertical speed, found by simply dividing change of height by time. Assume the curves to be sinusoidal; the ratio between the actual v_{max} and $\bar{v}$ becomes $\pi/2$. Unless the flight is made parallel to the wave crest, v_{max} will never be shown on the vertical speed indicator. The maximum figures read off the vertical speed indicator on the flight of July 26, all agree quite well with the computed values of $\bar{v}$. It seems justifiable to regard values of updrafts and downdrafts reported by pilots in connexion with mountain waves as being too low.

On Fig. 3 values of $\bar{v}$ in feet per minute, v_{max} in feet per minute, v_{max} in metres per second and a corrected value of v_{max} in metres per second are shown. A correction of $-0{\cdot}4$ metres per second is applied to v_{max} due to a possible incorrect trimming resulting in a mean ascent from A to B. It is a question

whether a correction, and if so what, has to be applied to v_{max} as the aircraft actually descended from B to C instead of continuing the mean ascent. The aircraft may have been subjected to a wave motion of which the distance from A to B is only a quarter of the wavelength. But one flight only cannot be used to track this possible wave, especially as long as the expected vertical speeds are of the same order as the errors in the method employed.

As shown on Fig. 2, at all levels below the troposphere the actual lapse rate is equal or very close to the moist-adiabatic lapse rate, except in the shallow inversion and the thin isothermal layer. Dividing the sounding curve into different layers, Scorer's parameter, l^2, is calculated within each layer.

$$l^2 = \frac{g\,(d\theta/dZ)}{\theta/U^2} - \frac{(d^2U/dZ^2)}{U},$$

where θ denotes the potential temperature.

The second term is small compared to the first term and is therefore neglected at all levels, except in the layer between 7,000 and 8,000 metres. Here the strong curvature of the wind profile makes the two terms nearly equal, but of different signs. l^2 decreases gradually up to this level, from where it starts increasing. This variation is mainly due to the wind profile. There is no deep stable layer with corresponding higher values of l^2 in the lower troposphere.

The wave motion encountered must be due to a rather complex interaction of different mountain peaks and ranges. Direct testing of theories will be difficult. Further investigations may show if the waves are of a real standing type and also reveal main features of their vertical and horizontal structures.

HIGH CLOUD STRUCTURE IN EQUATORIAL SOUTH-EAST ASIA

By L. W. LITTLEJOHNS

Introduction.—Aircraft reports are of great assistance in the daily preparation of analyses and forecasts in equatorial South-East Asia where surface and upper air observations are extremely sparse. In view of the increasing amount of high-altitude flying now taking place it was thought worth-while to compile statistical summaries of the incidence and height of high cloud found in this region.

Data analysed.—The data used were pilots' reports recorded at Changi, Butterworth and Negombo after flights above 25,000 feet during the period from February 1954 to August 1956. These were verbal reports, mainly from the crews of Canberra aircraft operating in the vicinity of Malaya, or in transit. The flights were not evenly distributed throughout the year (see Table I). The majority of the flights were at heights between 44,000 and 48,000 feet. All heights in these summaries are indicated heights—true heights are approximately 1,500 feet greater at 26,000 and 52,000 feet, and 2,000 feet greater between 35,000 and 45,000 feet[1].

Treatment of the data.—The flights were divided into six areas as demarcated in Figure 1, in which the airfields used and the number of flights in each area are also shown. Flights with only an isolated patch of high cloud were regarded as flights with no high cloud and were not included in the height and thickness summaries. Average heights of the base and top of each cloud layer in each area were assessed for all flights. The heights of the bases and tops did not vary

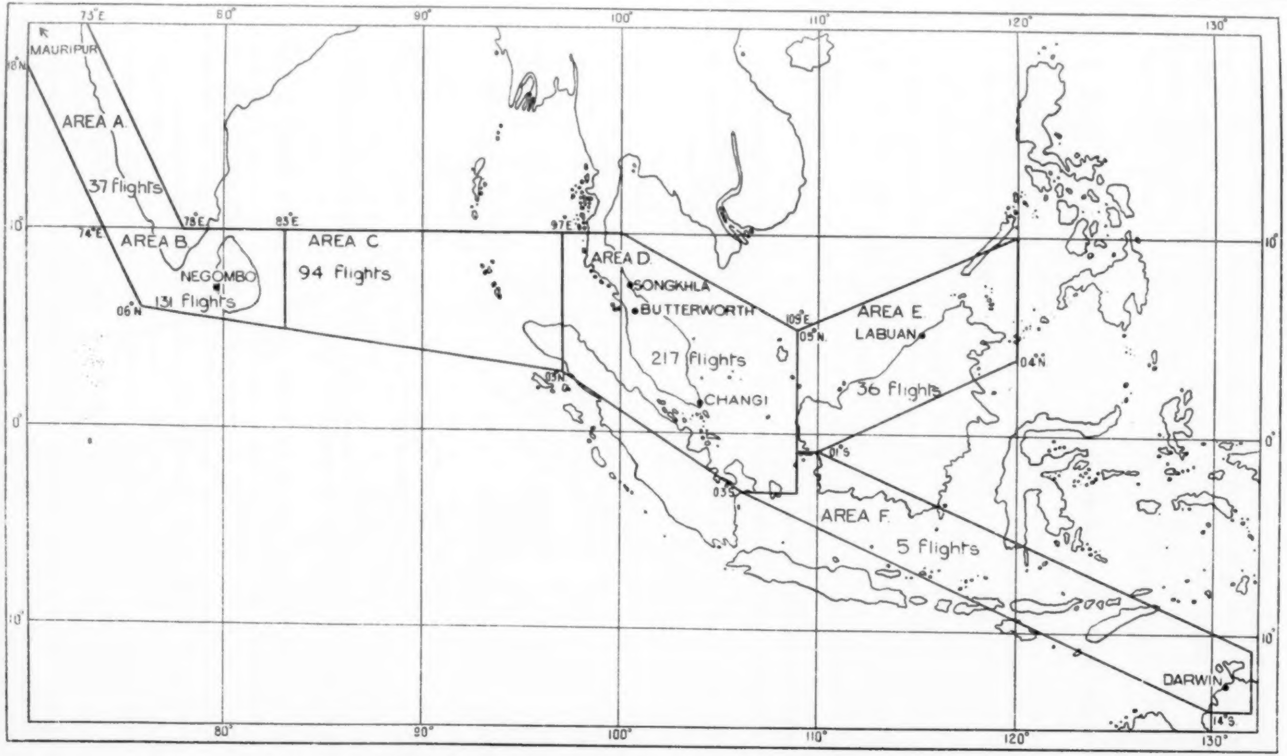

FIGURE I—AREAS COVERED IN ANALYSIS OF PILOTS' OBSERVATIONS FROM HIGH-ALTITUDE FLIGHTS

appreciably from place to place, and the heights found on ascent or descent could usually be accepted as representative of the area.

June and March were used to compare the thickness and height of high cloud in the "cloudier" and "less cloudy" seasons since a similar large number of reports was available in each month. November was selected as a transition month.

Results and discussion.—Between Mauripur and 10°N. high cloud occurred on only 2 flights in 15 from January to April, but it was found on 11 flights out of 13 from June to September. The seasonal variation, indicated by this small number of reports, is in agreement with that revealed by the analysis of pilots' reports from Comet flights over India in 1952 and 1953[2]. Of the five flights between Darwin and 110°E. there was one in April and one in May with little cloud, and one in December with extensive sheets of cirrostratus and large amounts of cumulonimbus. Pilots' reports from the above two areas have not been further considered, and the tables which follow refer only to the remaining four areas which lie between the parallels 10°N. and 03°S., and between the meridians 75°E. and 120°E.

Incidence of high cloud.—

TABLE I—PERCENTAGE FREQUENCY OF OCCURRENCE OF HIGH CLOUD

	Area (See Figure 1) B Ceylon	C Bay of Bengal	D Malaya	E North Borneo	B+C+D+E
			%		
Jan.	86 (7)	67 (3)	57 (7)	100 (1)	72 (18)
Feb.	47 (15)	89 (9)	73 (15)	100 (2)	68 (41)
March	54 (24)	50 (20)	61 (28)	100 (1)	56 (73)
Apr.	44 (9)	100 (5)	93 (14)	100 (2)	80 (30)
May	83 (12)	80 (10)	89 (28)	100 (5)	87 (55)
June	91 (23)	91 (12)	87 (32)	86 (7)	89 (74)
July	100 (6)	67 (3)	95 (21)	75 (4)	91 (34)
Aug.	77 (13)	91 (12)	79 (29)	75 (4)	81 (58)
Sept.	50 (4)	60 (5)	83 (12)	100 (5)	77 (26)
Oct.	71 (7)	57 (7)	92 (13)	33 (3)	73 (30)
Nov.	89 (9)	80 (5)	100 (8)	0 (1)	87 (23)
Dec.	50 (2)	67 (3)	80 (10)	100 (1)	75 (16)
Year	71 (131)	74 (94)	82 (217)	83 (36)	78 (478)

The number of reports available is shown in brackets.

Table I indicates that half of the flights across the Bay of Bengal in March were completely clear of high cloud; less than one in five were clear during the remainder of the year. Ship reports from the Bay of Bengal[3] confirm these minimum amounts of cloud in March. Over Ceylon high cloud was infrequent from February to April. At this time of year the north-east monsoon is weak, and the convergence zone between the monsoon and the equatorial westerlies normally lies to the south of Ceylon. The zone moves northwards over Malaya and the Bay of Bengal in April but does not actively affect Ceylon until the onset of the south-west monsoon in May. It usually returns to Ceylon and Malaya in October and November[4]. The frequency of high cloud increased during these transition months, but the maximum occurred in June and July. Little is known about the seasonal variation of wind at cirrus levels over Ceylon,

but there is a pronounced minimum in the mean wind at 50,000 feet over Singapore in March; at 40,000 feet the minimum extends to April. Over Songkhla (South Thailand, 100° 36′E., 07° 13′N.) minima at both heights occur from February to April[5]. The period of maximum frequency of high cloud did not entirely coincide with the period of strongest winds, July to September; lightest winds, however, were associated with least cloud. The incidence of high cloud did not appear to be closely related to the presence of large cumulus and cumulonimbus which were observed as shown in Table II. These clouds were usually described as isolated or scattered; only on rare occasions were they frequent or widespread.

TABLE II—FREQUENCY OF TOPS OF CUMULUS AND CUMULONIMBUS

	Height of tops (thousands of feet)				All heights	Total flights
	<30	30—39·9	40—49·9	>50		
	Number of occasions					
March	8	4	23	7	42	73
June	16	3	17	6	42	74
November	8	2	2	4	16	23
Year	115	28	113	32	288	478

Cumulus and cumulonimbus were reported equally in March and June, but the tops were higher in March when high cloud occurred least frequently. The more prevalent sheets of high cloud possibly obscured several large tops in June.

TABLE III—FREQUENCY OF OCCURRENCE OF MEDIUM CLOUD

	Medium cloud reported	Thickness exceeded 5,000 feet	Total flights
	Number of occasions		
March	4 (5)	3 (4)	73
June	26 (35)	11 (15)	74
November ...	13 (57)	9 (39)	23
Year	113 (24)	52 (11)	478

Percentage frequencies shown in brackets.

The percentage frequency of medium cloud (shown in Table III) was greatest in November; little variation occurred from May to September when the frequency was considerably in excess of that in March. It follows therefore that the factors which contribute to an absence of high cloud may also lead to an absence of medium cloud, but they probably do not affect the incidence of large cumulus or cumulonimbus.

Types of high cloud.—

TABLE IV—FREQUENCY OF TYPES OF HIGH CLOUD

	Nil	Cirrus	Cirro-stratus	Cirro-cumulus	All types	Type un-specified	Two layers of high cloud
	Number of occasions						
March	32	28	10	1	39	3	1
June	8	39	32	0	71	0	5
November	3	8	9	1	18	2	0
Year	106	249	117	3	369	16	13

Table IV shows the number of occasions on which the different types of high cloud were reported. In March high cloud was most frequently in the form of cirrus. In June and November the denser sheets of cirrostratus were reported almost as often as cirrus. Cirrocumulus was extremely rare. Two layers of high cloud were seldom reported, but may of course have existed more frequently.

Bases and tops of high cloud.—

TABLE V—FREQUENCY OF HEIGHTS OF BASES OF HIGH CLOUD (CIRRUS, Ci; CIRROSTRATUS, Cs)

	Height (thousands of feet)															
	Merged with medium cloud		25—29·9		30—34·9		35—39·9		40—44·9		45—49·9		>50		Number reported	
	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs
	Number of occasions															
March	1	0	0	0	3	2	15	1	3	3	2	1	1	0	25	7
June	1	1	7	2	4	2	10	6	4	5	5	8	1	0	32	24
Nov.	0	0	0	4	3	1	3	1	0	0	1	0	0	0	7	6
Year	2	6	14	10	29	13	81	20	46	16	25	13	2	1	199	79

TABLE VI—FREQUENCY OF HEIGHTS OF TOPS OF HIGH CLOUD (CIRRUS, Ci; CIRROSTRATUS, Cs)

	Height (thousands of feet)										Number reported	
	30—34·9		35—39·9		40—44·9		45—49·9		50—54·9			
	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs	Ci	Cs
	Number of occasions											
March	0	0	2	1	9	2	11	6	4	0	26	9
June	2	0	2	1	15	4	16	17	3	1	38	23
Nov.	1	0	2	0	1	1	2	7	0	1	6	9
Year	9	0	21	7	73	24	84	56	14	7	201	94

The base of cirrus (see Table V) was most frequently reported between 35,000 and 40,000 feet. In March the occurrence of the greatest frequency (mode) in this range was well marked, but over the remainder of the year there was more variation in the reported bases. The bases of cirrostratus were distributed with fairly equal frequency over a large range of height.

Table VI shows that approximately 80 per cent of the reported tops of both cirrus and cirrostratus were between 40,000 and 50,000 feet; the cirrus tops were spread evenly over this range, but the cirrostratus tops were more frequent between 45,000 and 50,000 feet especially in June and November. The maximum tropospheric wind over Singapore usually lies within this latter height range which is some 5,000 to 10,000 feet below the equatorial tropopause. James[6] also found, in middle latitudes, a rather similar relationship between the height of cirrus cloud tops and the height of the tropopause, and noted that other work on the subject suggests that the top of cirrus cloud is closely associated with the height of the horizontal wind maximum.

Thickness.—Unfortunately there were many occasions when the base or tops were unknown, and for which no reliable estimates can be made. The number of these occasions is shown in Table VII. Limiting values for thickness in some cases can, however, be determined from Table VIII which relates the missing observations to flight levels.

[*To face p. 176.*

Photograph reproduced by kind permission of The Belfast Telegraph

MAIL FOR "WEATHER RECORDER"

This photograph, taken from a Royal Air Force aircraft of Coastal Command on 20 December 1957, shows the bomb doors open, and a canister containing Christmas mail with parachute attached being dropped for *Weather Recorder*. The ship's logbook showed that the wind at the time was west-north-west force 9. The ship is obviously "lying stopped" or steaming very slowly.

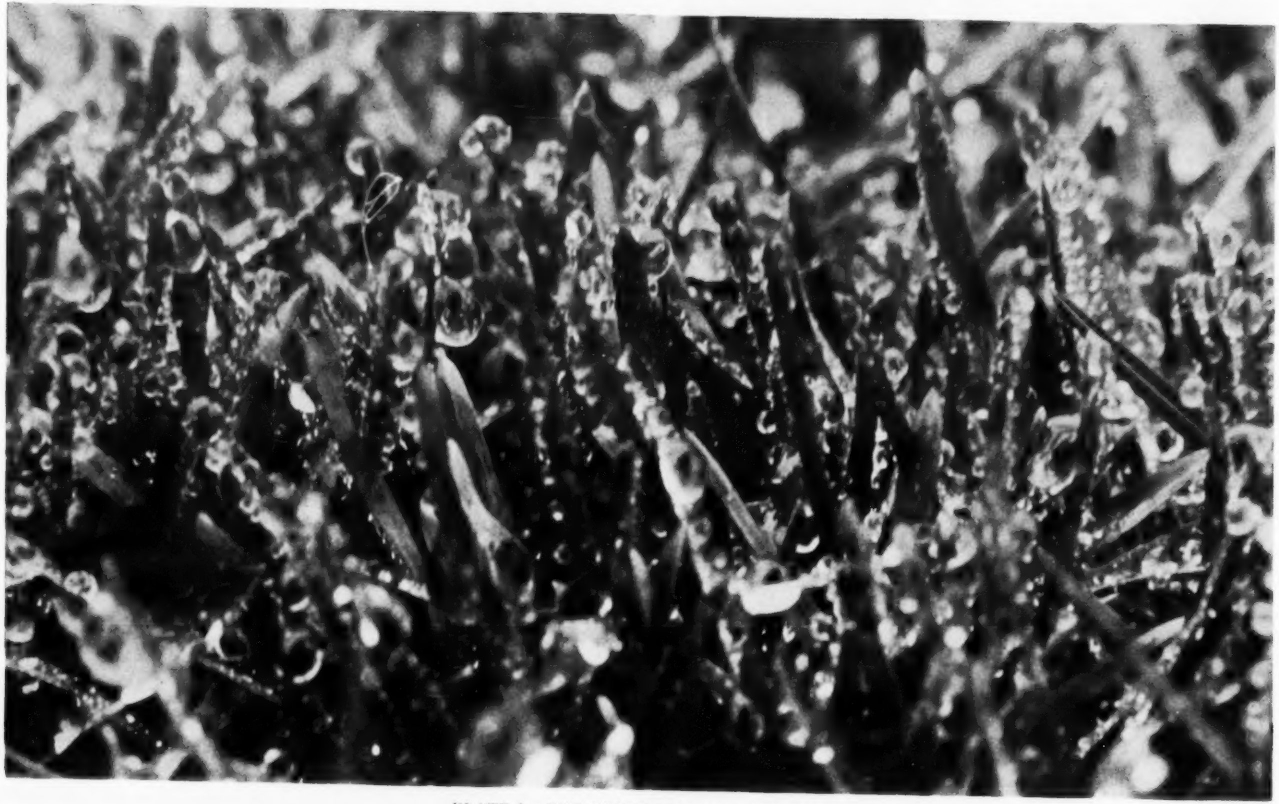

PLATE I—FOG PRECIPITATION ON GRASS

(see p. 161)

Photograph by I. P. Long

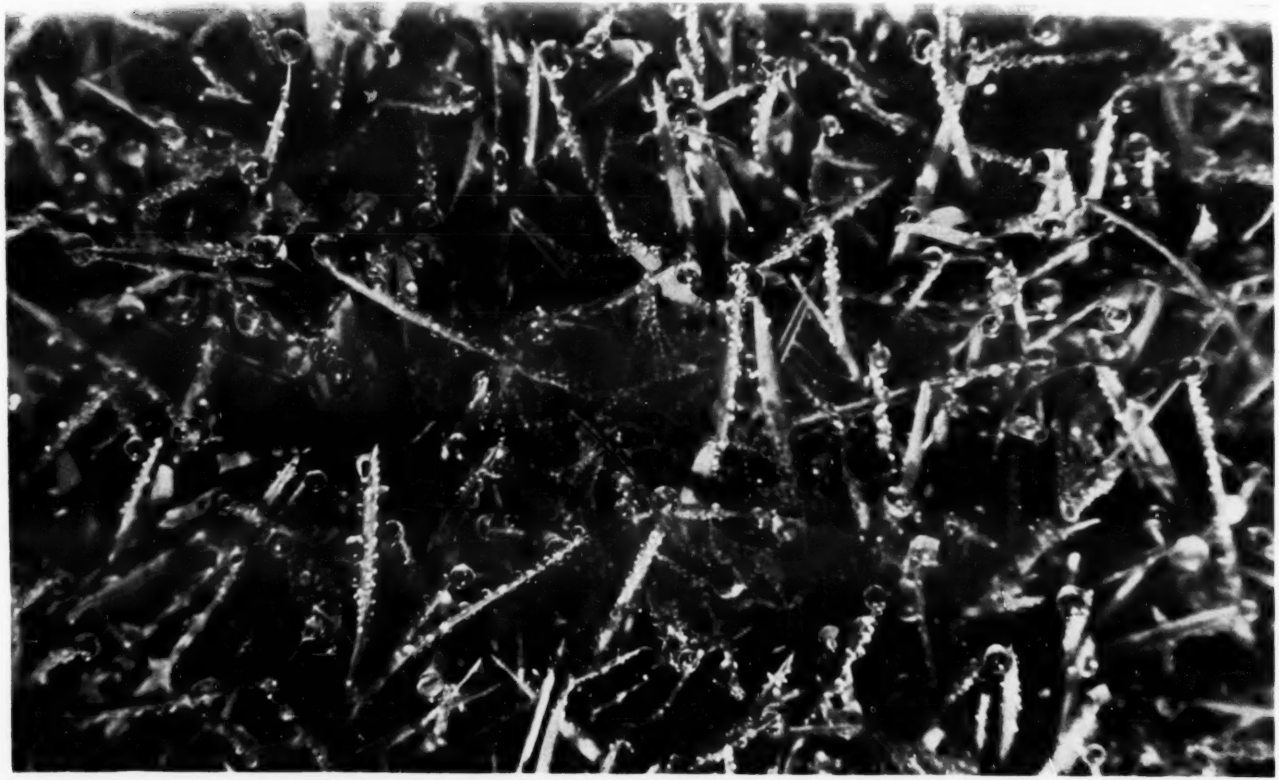

PLATE II—DEW, SMALL DROPS: AND GUTTATION LARGE DROPS, ON GRASS

(see p. 162)

Photograph by I. F. Long

Photograph by I. F. Long

PLATE III—GUTTATION DROPS ON GRASS

(see p. 162)

TABLE VII—NUMBER OF HIGH CLOUD BASES OR TOPS NOT REPORTED (CIRRUS, Ci; CIRROSTRATUS, Cs)

	Bases			Tops		
	Ci	Cs	Type not specified	Ci	Cs	Type not specified
	Number of occasions					
March	3	3	3	2	1	3
June	6	9	0	2	8	0
November	1	3	2	2	0	2
Year	49	39	16	49	22	16

TABLE VIII—FREQUENCY OF UNREPORTED HIGH CLOUD BASES OR TOPS AT VARIOUS FLIGHT LEVELS FOR ALL MONTHS (CIRRUS, Ci; CIRROSTRATUS, Cs)

		Flight level (thousands of feet)					
		<35	35—39·9	40—44·9	45—49·9	≥50	All levels
		Number of occasions					
Base unknown, flight above cloud layer	Ci	0	4	15	21	5	45
	Cs	0	3	10	20	2	35
Top unknown, flight below cloud layer	Ci	5	20	10	10	0	45
	Cs	2	3	3	10	0	18
Base and top unknown, flight in cloud	Ci	0	2	2	0	0	4
	Cs	2	0	0	2	0	4
High cloud reported, but no details of type or height given		3	1	9	3	0	16

The 33 cases of flights below a cloud layer at heights above 40,000 feet must have been occasions of shallow cloud. It can be assumed that the average cloud thickness on the 20 highest flights was 5,000 feet or less, and that on the 13 next highest it was 10,000 feet or less. On the 16 occasions when no details

TABLE IX—FREQUENCY OF THICKNESSES OF HIGH CLOUD (ALL MONTHS)

Cloud Base (thousands of feet)	Thickness (feet) 2,500	5,000	10,000	15,000	20,000	25,000
CIRRUS	*Number of occasions*					
25—29·9	0	4	1	7	1	1
30—34·9	5	5	10	7 (+2)	0	0
35—39·9	12	19	27	3 (+2)	0	0
40—44·9	25 (+3)	15 (+4)	0(+3)	0	0	0
45—49·9	9 (+5)	6 (+5)	0	0	0	0
≥50	1	0	0	0	0	0
Unknown (cloud too far from aircraft)	0 (+8)	0 (+8)	0	0	0	0
Total	47 (+16)	49 (+17)	38 (+3)	17 (+4)	1	1
CIRROSTRATUS	*Number of occasions*					
25—29·9	0	0	0	1 (+2)	14	1
30—34·9	0	2	4	5	2	0
35—39·9	2	10	5	2 (+2)	0	0
40—44·9	0 (+1)	12 (+1)	0 (+1)	0	0	0
45—49·9	2 (+5)	0 (+5)	0	0	0	0
≥50	0	0	0	0	0	0
Total	4 (+6)	24 (+6)	9 (+1)	8 (+4)	16	1

Number reported: Cirrus 153 (+40) Cirrostratus 62 (+17).
Number with base and/or top unknown: Cirrus 110 (−40) Cirrostratus 57 (−17).
The figures in brackets refer to estimated thicknesses.

were given the cloud was usually too far from the aircraft for any estimate of its height to be made. It is unlikely that the cloud thickness exceeded 5,000 feet on these occasions. On the 8 flights in cloud the thickness probably exceeded 12,500 feet, otherwise the flight levels would have been changed to avoid the cloud. These estimated thicknesses are included (in brackets) in Table IX which shows the frequency of specified thicknesses of high cloud.

On approximately half the 263 occasions of cirrus the thickness was from 2,500 to 5,000 feet. The proportion of cirrostratus with this thickness was only one third, and a similar proportion consisted of thicknesses from 10,000 to 20,000 feet. There were 16 reports of cirrostratus being 20,000 feet thick, 5 of these being in November.

Summary.—In the region from South India to North Borneo high cloud was most prevalent from May to July, extending to April and August in some areas, with a further secondary maximum in November. Cirrostratus occurred almost as often as cirrus in the cloudier periods. Cirrocumulus was seldom encountered. Most of the tops lay between 40,000 and 50,000 feet, cirrostratus tops being slightly higher than cirrus. In March the base of cirrus was most frequently between 35,000 and 40,000 feet; in other months the bases of cirrus and cirrostratus were spread over a very large range of height.

Other interesting features in the pilots' observations.—*Cumulus or cumulonimbus.*—Cloud development over the sea in the vicinity of Malaya usually reaches a maximum during the night, and the cumulus normally disappears during the morning. This sequence was observed not to occur on three occasions. On 2 February 1956 and 12 June 1956 lines of cumulonimbus were reported to have developed over Malacca Straits (some 20 to 60 miles from the coast) between 0800 and 1100 hours, local time. On 16 May 1956 large cumulus was developing over the South China Sea off the coast of Trengganu between 0900 and 1000 hours, local time.

On one of the rare occasions of night flying (18 March 1955) scattered cumulonimbus extended along the west coast of Malaya; the effect of the associated lightning, observed from 48,000 feet, was described as most impressive, being compared with flak. On another night flight (5 April 1955) a Canberra penetrated a cumulonimbus top at 45,000 feet and was rapidly wafted up to 49,000 feet where the low temperature caused a "flame-out". Vigorous St. Elmos fire and moderate turbulence were experienced.

Probably the most severe conditions encountered (this report was by a pilot with fourteen years flying experience) were on a flight from Negombo to Changi on 25 April 1956. For much of the Bay crossing the aircraft was in cirrostratus at 40,000–45,000 feet. Cumulonimbus tops were encountered about mid-Bay, and turbulence, which had been slight to moderate, became extremely severe and was accompanied with hail. Damage was caused to the aircraft. Hail is a rarity in this equatorial region, but on the following day there was a surface report of hail at Terampa in the Anambas Islands.

Cumulonimbus tops, and indeed all cloud, were avoided when possible, and this may well account for the fact that there were more reports of turbulence in clear air than in cloud (see Table X).

Turbulence.—

Turbulence was experienced on at least 1 flight in 4; it was moderate or severe on about 1 flight in 8. Some of the occasions of turbulence occurred on

the climb or descent otherwise frequency in the various height ranges would probably have been proportional to the number of flights in each height range.

TABLE X—FREQUENCY OF OCCURRENCE OF TURBULENCE

	Height (thousands of feet)								All heights	
	<40		40—44·9		45—49·9		>50			
	(*a*)	(*b*)	(*a*)	(*b*)	(*a*)	(*b*)	(*a*)	(*b*)	(*a*)	(*b*)
	Number of occasions									
March	3 (2)	2 (1)	1	0	3	4 (1)	0	0	7 (2)	6 (2)
June	4 (2)	2 (1)	2 (1)	1	5 (3)	3 (2)	2 (1)	0	13 (7)	6 (3)
Nov.	0	2 (1)	0	2 (1)	2 (2)	2 (2)	0	0	2 (2)	6 (4)
Year	17 (6)	15 (10)	13 (5)	11 (3)	39 (20)	24 (11)	6 (2)	0	75 (33)	50 (24)

(*a*), clear air. (*b*), in cloud. Figures in brackets are when turbulence was moderate or severe.

Icing.—Light airframe icing was reported on 13 occasions; 9 of these were at heights above 40,000 feet.

Contrails.—The frequency of occurrence of contrails is given in Table XI.

TABLE XI—FREQUENCY OF OCCURRENCE OF CONTRAILS

	Height (thousands of feet)					
	<30	30—34·9	35—39·9	40—44·9	45—49·9	>50
	Number of occasions					
All reports	1	4	5	13	30	2
Dense and persistent ...	0	1	1	5	15	2

There were 2 flights between 30,000 and 40,000 feet, and 3 flights above 40,000 feet when it was known that contrails were not made, but on the majority of flights it was not possible to say whether or not contrails were made.

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METEOROLOGICAL OFFICE DISCUSSION

Forecasting precipitation

The Meteorological Office Discussion at the Royal Society of Arts on Monday, 18 February 1958 was on the subject of forecasting precipitation.

Mr. H. H. Lamb spoke first, dealing with the problem of whether rain, sleet, snow or hail should be expected. Conditions for hail are special, depending primarily on the vertical instability being enough to give the strong up-currents required to support growing hailstones. Those particularly concerned

with hail were recommended to read the recently reviewed book by Flora[1]. Extreme hailstones measure several inches across and weigh several pounds. The United States Weather Bureau's Severe Weather Warning Centre, operating in the Great Plains where hail and tornado risks are greatest, finds that large hail is commonest when the "wet-bulb freezing level" is about 8,000 feet (2,500 metres approximately) above the ground. This corresponds quite well with experience in Britain in summer and in the Mediterranean in winter, where the worst hail occurs in unstable air with 1,000–500-millibar thicknesses about 5,500 metres. With higher temperatures than those corresponding to this thickness much of the hailstones melts during descent, and the smaller types of hail would melt with rather lower thicknesses.

To decide whether snow will melt before reaching the earth, one really needs to know not only the height of the freezing level but also the initial size of the individual snowflakes and mass of frozen water involved, its starting temperature or the level at which melting begins and the detailed thermal structure of the layers between this level and the ground. This thermal structure is constantly changing under the influence (amongst other things) of the varying intensity of the precipitation and attendant evaporation cooling.

In practice, of course, one must do one's best with the available tools in the forecaster's armoury. One can do a good deal with charts of 1000–500-millibar thickness alone. Reference was made to two papers[2,3], reporting studies of associations between the change-over from rain to snow and 1,000–500-millibar thickness, 1,000–700-millibar thickness, freezing level and surface temperature. The results for 1,000–700-millibar thickness were actually worked up mainly for the more maritime districts of the British Isles, and should be applied with caution in more extensive land areas.

Chances of rain or snow falling appeared from examination of 2,000 cases to be about equal at low-level inland stations in winter with 1,000–500-millibar thicknesses around 5,280 metres. The probabilities tilted sharply in favour of rain or snow according as the thickness increased or decreased much from this value. Important special cases arose in winter when long-continued precipitation was expected to fall from frontal medium cloud through air initially dry enough to give no low cloud. Cooling by evaporation from the falling rain progressively lowered the temperatures and the thickness: in one case in 1942 rain began with freezing level over 5,000 feet (1,500 metres) and thickness 5,400 metres, but ultimately changed over to snow which became deep before precipitation ceased. Once a snow cover was established there was a considerable chance of snow flurries from fairly low clouds, for example, stratocumulus beneath a subsidence inversion, with 1,000–500-millibar thicknesses up to 5,400 metres, though any precipitation originating in frontal medium cloud with this thickness would probably fall as rain.

In our more maritime districts, on small islands, and at sea where low temperatures generally imply unstable lapse rates, the thickness giving a fifty–fifty chance of snow is lower than the figure for inland districts. In these regions in winter and for late spring or early autumn snow inland, the critical thickness may be 5,250 metres or below. Corresponding criteria for snow at various upland places and on slopes of different aspect might profitably be derived from similar statistical investigations at the forecasting offices concerned with different hill districts.

In the ensuing discussion, *Mr. R. F. Jones* pointed out that hail need not be entirely supported by up-currents, since considerable amounts of ice could accrue to a hailstone during its fall through cloud.

Mr. Buchanan preferred the use of 1,000–700-millibar thicknesses and demonstrated a diagram on which a set of curves showed the percentage frequency of precipitation in frozen form plotted against thickness for different heights above sea level. This could be a valuable aid to precision in forecasts of snow on high ground: ideally the forecaster should be able to specify "snow above the (say) 500- or 1,000-foot level".

Mr. Craddock gave a warning that if one investigated in terms of two variables, in this case observing how the critical thickness value shifted when height above sea level also varied, one needed larger samples to avoid the risk of being misled by apparent associations which can arise by chance. This was an example of multiple regression analysis.

Mr. Veryard reminded the meeting of the old rule that snow should be expected if the initial surface temperature were below 40°F. The average surface temperature in inland districts corresponding to the critical thickness of 5,280 metres was about 38°F.

Mr. Wilson quoted a case noted at Renfrew when snow began when the temperature reached 39°F. Three hours later it was 33°F.

Mr. May asked whether the case of long-continued precipitation through dry air modifying the thickness could lead to snowfall over any great area, since presumably it would be a narrow belt of precipitation along a quasi-stationary front. In reply Mr. Lamb remarked that a belt at least 150 miles broad over southern England got heavy snowfall in this way at Christmas 1927.

Mr. Tunnell emphasized that the distribution of water vapour with height needed to be studied in this connexion. He pleaded for use of wet-bulb potential temperatures and regular study of the hydrolapse.

Mr. Miles added that in situations where warm air overran a shallow wedge of cold air, it might be that the lighter the precipitation the more liable it would be to reach the ground unmelted. If the precipitation melted completely, however, before reaching the surface freezing layer, he did not believe it could ever freeze again before reaching the ground.

Mr. Walker said that at Manby the first snow this winter fell with thickness as high as 5,340 metres. This was granular snow which became three inches deep before going over to ordinary snowflakes.

Mr. Gold asked Mr. Lamb to make it clear that forecast (not previously reported) values of thickness must be used in deciding whether snow should be forecast at a given place. Snow already falling in the same airstream upwind might be the best indicator of all. If the precipitation upwind were rain, one must be sure of a materially lower surface temperature before forecasting snow at one's own station.

The problem of research into frontal rainfall

Opening the second part of the discussion Mr. C. E. Wallington said that forecasting frontal rainfall may be considered as two distinct problems; one centres

on the movement of fronts, the other concerns the distribution of rainfall with whatever front is being considered. In practice the movement of fronts is dealt with fairly methodically, and with moderate success. But comparatively little is known about forecasting the shape and size of the rain area associated with any particular front. Not enough is known about the mesoscale atmospheric motions which take place in the frontal zone; these mesoscale motions are particularly awkward for research. Furthermore, little observational experience has so far been accrued of motion on this scale. A mesoscale feature is too large to be adequately observed from any particular spot and too small to be portrayed by the routine synoptic charts. On 2 September 1949, for example, the rain area ahead of a warm front appeared as a broad belt. But records of measured rainfall per hour revealed, not a simple broad rain-belt, but several tongues of rainfall, as illustrated in Figure 1.

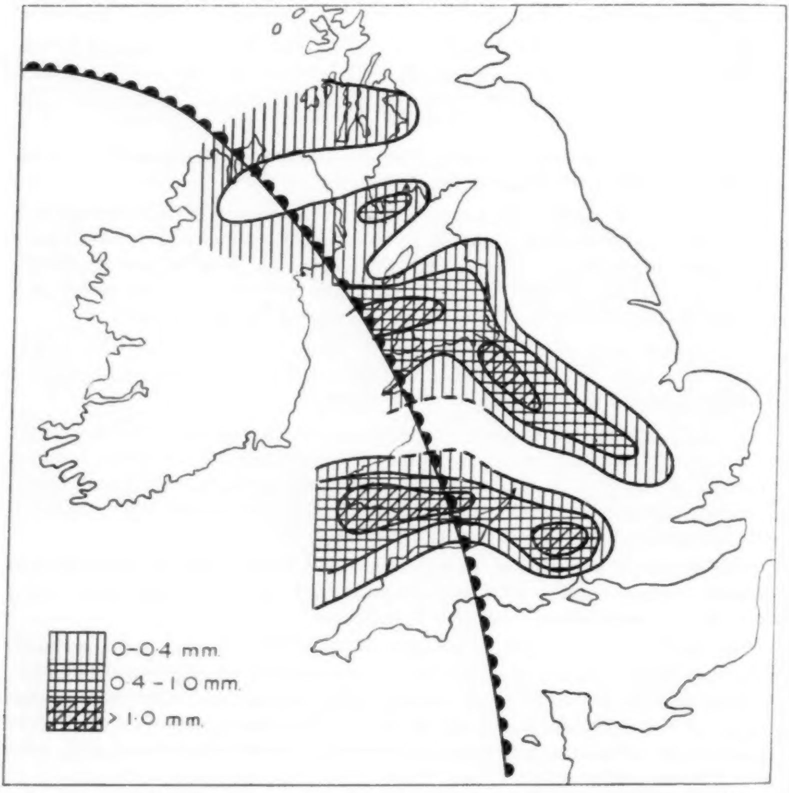

FIGURE 1—WARM-FRONT RAINFALL, 0300–0400 G.M.T., 2 SEPTEMBER 1948.
The mesoscale features illustrated on this hourly rainfall chart maintained too much continuity to be fully accounted for by local peculiarities or by subjective drawing of the charts.

Two problems arise from these rainfall observations. First, how does this type of distribution arise? It maintained too much continuity to be explained entirely by local effects or by subjective drawing of the hourly rainfall charts.

Secondly, how can we account for the reported rates of rainfall? It would be of interest to measure or calculate fields of vertical motion in detail. But this is difficult; the network of upper air observations is too coarse, and methods applicable to the study of broad-scale motions are of very doubtful accuracy when applied to regions in which stability is small and ageostrophic motion is important. So for the moment it seems more profitable to study more patterns of hourly rainfall with the object of accruing enough experience to devise and test more elaborate concepts than the basic frontal models.

Warm-frontal waves.—Perhaps we can obtain an insight into the dynamics of rain-belts by studying the relationship between rates of rainfall and small frontal waves. Warm frontal waves can often be classed as mesoscale phenomena and we have acquired some familiarity with their characteristics. Their formation is usually associated with a confluent ridge in the thickness lines. We know by experience and by theoretical reasoning that in such a situation "cyclonic development"—or ascending motion in the troposphere—is likely close to the warm front and some distance from the depression centre. Although it is not too difficult to recognize this warm-frontal wave type of situation, it is practically impossible to predict precisely when or whereabouts within the "development" region a wave will form. More experience and theoretical reasoning shows that stability plays an important part in the process. Vertical motion is damped by stability, especially in processes on the meso- and local scales. But in assessing this damping we should consider not just the static stability—that is the stability which can be seen at a glance on the tephigram—but the hydrodynamic stability, which takes into account the distribution of both temperature and wind. It is important that these items should be considered together.

Hydrodynamic instability.—Suppose that, in an airstream in which the wind speed increases with height, a parcel of air is displaced upwards without seriously distorting the general pressure and temperature patterns. If the airstream is statically stable then it might be supposed that the displaced parcel would promptly return towards its original level. But such a supposition neglects the wind shear. The displaced air has a lower speed than that required for geostrophic flow at its new level. So the parcel is diverted towards lower pressure. But the increase of wind with height owes its existence to a thermal field in which temperature decreases towards the region of low pressure. Thus the transverse displacement takes the disturbed parcel of air into a progressively colder environment, and the effective, or hydrodynamic, stability is less than the static stability. In fact this is one of the variety of ways in which hydrodynamic instability can occur. Unfortunately, we do not yet know enough about the concept of hydrodynamic instability to use it in routine forecasting. For the present, all we can do is to realize that many situations may not be quite as stable as we think they are.

Hourly rainfall patterns.—Vertical motion imposed by the broad-scale pressure and temperature fields is damped by hydrodynamic stability. But suppose that a damped upward motion is just sufficient to produce saturation. Such saturation will immediately reduce the stability and the upward motion will receive a sudden impetus.

So in the practical problem of locating or predicting small regions of ascending air there are several complications of which we can be aware but which we cannot yet resolve. The magnitude of such vertical motion depends upon the precise details of the thickness and contour charts, the hydrodynamic stability and the humidity. In view of these complications it may well be that a cyclonic "development" region contains not just one but several separate cells of rising air. Perhaps the more extensive cells betray their presence by distorting the frontal pattern while the intensive features generate frontal rainfall from behind the synoptic scenes.

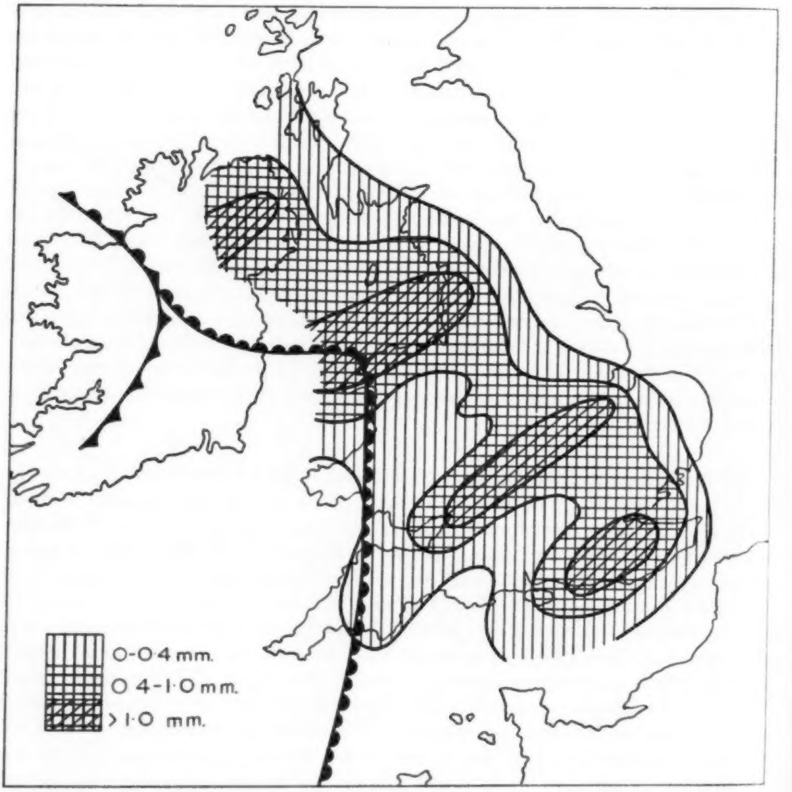

FIGURE 2—WARM-FRONT RAINFALL, 2100–2200 G.M.T., 1 JANUARY 1952.

The warm-front wave may have been a synoptic manifestation of just one of several cells in a broad development region.

The warm-front wave illustrated in Figure 2 may well have been a synoptic manifestation of just one of several cells in a broad "development" region. The rainfall pattern is suggestive of other cells, and this type of distribution is not uncommon. Figure 3 shows another situation with at least two separate cells of rainfall preceding a small wave across England. This cellular type of dis-

tribution is not always associated with small frontal waves. The situation illustrated in Figure 4, for example, shows three distinct cells of heavy rainfall with no apparent distortion of the frontal system. This and other charts of hourly rainfall suggest that slowly rising air in frontal zones is augmented in places by some sort of instability, either hydrodynamic instability in patches or instability of waves on wavelengths of about 100 to 300 miles. But before devising too elaborate a hypothesis for explaining the distribution and rates of frontal rainfall observed it seems advisable to acquire a greater familiarity with charts of hourly rainfall.

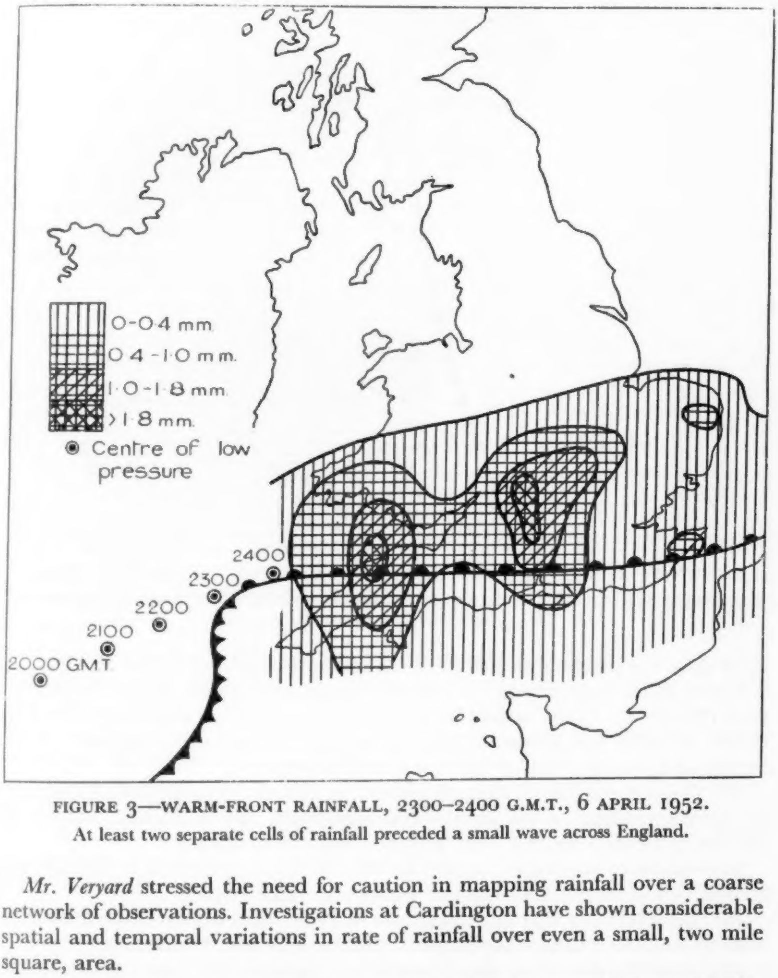

FIGURE 3—WARM-FRONT RAINFALL, 2300–2400 G.M.T., 6 APRIL 1952.
At least two separate cells of rainfall preceded a small wave across England.

Mr. Veryard stressed the need for caution in mapping rainfall over a coarse network of observations. Investigations at Cardington have shown considerable spatial and temporal variations in rate of rainfall over even a small, two mile square, area.

Later in the discussion *Mr. Cottis* and *Mr. Smith* also stressed the variability of rates of rainfall over a small area. Mr. Wallington replied that such varia-

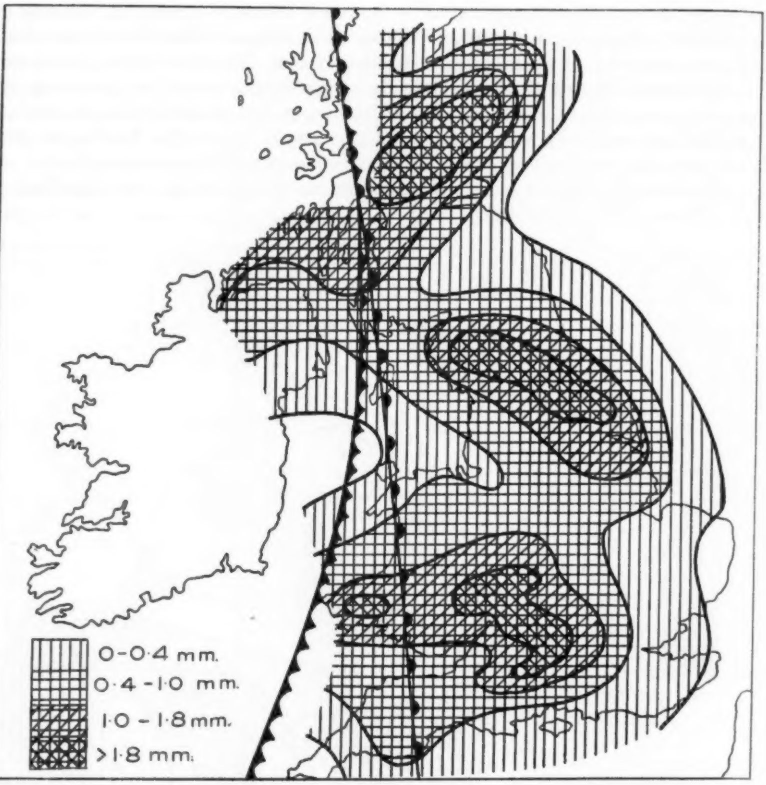

FIGURE 4—WARM-FRONT RAINFALL, 0100–0200 G.M.T., 31 JANUARY 1952.

The cellular type of rainfall distribution is not always associated with distortion of the frontal system into small waves.

bility does not preclude detection of the mesoscale features in the distribution of hourly rainfall on occasions when these mesoscale features predominate over local effects. The charts he had shown were extracted from sequences of hourly charts on which the mesoscale features maintained too much continuity to be explained by local effects or by subjective drawing.

Mr. Craddock considered that, although it is difficult to judge the relationship between variations on the micro- and meso-sides, the distinctive features of the hourly rainfall patterns were probably not due to chance.

In response to an enquiry by *Mr. Ratcliff*, *Mr. Harper* said that it was difficult to deduce rate of rainfall from the intensity of radar echoes.

Mr. Lamb recalled that Prof. Bergeron had identified frontal rainfall features over Sweden on a similar scale to that discussed by Mr. Wallington.

Mr. Saunders described the relationships between the amount of frontal rainfall received in south-west England and various parameters such as upwind pressure tendencies and the direction of the warm-sector isobars.

Mr. Tunnell called attention to the effects of turbulence and convective cells in warm frontal regions.

Mr. Jefferson said that distinctive mesoscale features could often be identified by careful analysis of routine synoptic charts.

The timing of precipitation

Opening the final part of the discussion, Mr. B. Ramsey said that one of the first points to be considered in the timing of precipitation is the forecasting of whether the depression concerned will pass to north or south of the area. With a depression passing to the south, timing of precipitation becomes a matter of forecasting the general movement of the precipitation area of the low. With centres passing to the North, the shear hodograph gives an indication of whether the fronts are anafronts or katafronts, with their wide variations in precipitation areas, for example, a warm anafront gives a wide area of rain well ahead of the surface position of the front. A change of shear could vitally affect the timing of precipitation. A point to note, mainly with warm fronts, is the state of the cold air ahead. A stable dry cold mass will inhibit precipitation for some time, due to the evaporation of rain or snow falling into it.

A good guide to the movement of cold fronts is the mean 600-millibar wind normal to the front, again due consideration being given to whether the front is ana- or kata-, the former giving marked rain behind the front. Open waves are closely associated with the 500-millibar flow aloft and move at about half the speed of this flow. Rain areas, however, appear to move in fairly close agreement with the 700-millibar flow.

Shower activity has its problems too and here the question of season arises. In winter, due to lack of insolation, showers will probably not develop overland and the only showers expected are advected from the sea. Another point is—how strong does the gradient have to be to maintain shower activity all night over a cold land area? Belfast, for instance, seems to need about a 50-knot westerly gradient and 25–30 knots from north-west, but oddly enough, only 20 knots from 330° maintains snow showers all night. Did anyone present use similar criteria for other areas?

Showers in spring and summer often do not occur over the sea due to the colder water, and hence over windward coastal areas too, although at the same time they might well be active inland. The timing of showers then becomes a matter of forecasting the wind direction. Sea-breezes are notable for the removal of showers from coastal areas. Summer showers can be difficult to forecast. A point noted at Aldergrove, and probably elsewhere inland, is the spell of showers often fairly early in the day in a north-westerly summer stream, and then no more for the rest of the day. Does the explanation lie in the fact that, with the evaporation of dew in the morning the condensation level is lower than in the afternoon when, with a higher condensation level, drier ambient air may be more easily entrained?

The timing of snow has its difficulties. These are, chiefly, the forecasting of the height at which snow will fall on hills and the change from rain to snow in frontal precipitation. In the former case a useful guide is the height of the wet-bulb freezing level in the cold air—the drier and colder the air, the lower down

will snow fall. This also applies to rain turning to snow but, in addition, snow seems practically certain with a total thickness of 5,220 metres or less. Exceptions to the foregoing occur most frequently on windward coasts, depending on the sea temperature.

The distribution of rainfall.—This is one of the most complex and difficult of meteorological problems. A check was made of the 1957 rainfall at several gauges around Belfast. Those just to the east of the hills gave between 40 and 44 inches while Aldergrove and Nutts Corner, both to west of the hills, gave 34 and 38 inches respectively. With a prevailing westerly or south-westerly wind, this means that the lee stations experience greater rainfall than the windward stations. Corby[4] shows that under suitable conditions the wave crest may be displaced downwind of the mountain ridge by several miles. Thus, lifting would continue beyond the hills, possibly resulting in heavier rainfall to the lee. It would require a dense network of gauges in a suitable area to confirm this. With regard to shower distribution, Aldergrove seems to escape showers in a north-westerly stream, while Nutts Corner, to the south-east, and places upwind are more affected. This could be the effect of a large lee wave produced by the Sperrin range, a feature which may also account for Aldergrove's lower average rainfall compared with neighbouring gauges.

In the course of discussion, *Mr. Lamb* said that in winter, showers had been found to be ten times more frequent at Lerwick than at Mildenhall and that in all maritime districts the lower the total thickness the greater the chance of showers. In continental areas this does not apply. The probable explanation of the greater persistence of snow showers at night, in contrast to rain showers, is that the cold air needed to produce snow is normally the more unstable.

Mr. McCaffery said that one method used by the Central Forecasting Office for the transport of rain was to use the wind at the level of the rain-producing cloud, frequently the 700-millibar wind, with some added notions of development taking place. No numerical estimates were made.

Mr. Gold said he thought it impossible to follow the physics from the beginning of snowfall but one must go to the final patterns and then work back to what the initial situation was. He mentioned the difference between rainfall in January 1958 at Kew (49 millimetres) and Golders Green (69 millimetres). There was need of a thorough network of gauges for compiling distribution charts. Both dynamical irregularities and irregularities in temperature and humidity might be important in controlling the distribution.

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OBITUARY

Dr. A. J. Bamford, M.C., V.D., Ph.D., M.A.—Dr. Alec Joscelyne Bamford died at Worthing, Sussex, on November 19, 1957, in his 73rd year, after a short illness.

Dr. Bamford was educated at Malvern and at Emmanuel College, Cambridge. After graduating, he obtained a post at the Colombo Observatory, as assistant to Mr. H. O. Barnard, the Assistant Surveyor-General of Ceylon, who was also Superintendent of the recently founded Observatory. Dr. Bamford landed in Ceylon in November 1908. He was the first full-time scientific officer of the Observatory and, when Mr. Barnard retired, he became its first full-time Superintendent, in January 1913.

Under the direction of Dr. Bamford, more rigorous methods of checking the observations taken at the meteorological and rainfall stations in Ceylon and of testing instruments were adopted. After returning from active service, he started a programme of pilot balloon wind observations and, later, a wireless time service for the benefit of shipping. He also devised a method of forecasting flood data for the Kelari River at Colombo from the rainfall figures reported daily in the Kelari Valley. This method was adopted officially by the Ceylon Government for flood warnings at Colombo.

Dr. Bamford carried out many investigations chiefly on the meteorology of Ceylon and published his results in scientific journals in Ceylon and Europe. In addition to his Observatory duties, on several occasions he acted as Professor or Lecturer in Physics at the University College, Colombo.

During the First World War, Dr. Bamford served with the Armoured Cars in German East Africa, and was later employed on sound ranging and army survey work in Palestine and Arabia. He received the Military Cross, and was twice mentioned in despatches. In 1919 he was demobilized with the rank of Captain.

Throughout his service in Ceylon, Dr. Bamford took a great interest in the Ceylon Planters' Rifle Corps. Joining as a rifleman, he retired from the Corps in 1931, on his final departure from Ceylon, as a Major.

On his return to England Dr. Bamford was for some years engaged in teaching, but in 1941 he accepted a post in the Meteorological Office, and was posted to the Marine Branch, which had been evacuated to Stonehouse, in Gloucestershire. There he was mainly engaged on the principal war-time activity of the Branch, the production of Meteorological Atlases covering all the oceans of the world.

Both before and after his arrival at Stonehouse, Dr. Bamford served with the Home Guard. He retired from the Meteorological Office in 1946, and moved to Ferring, in Sussex, where his wife died in 1954. He leaves a son and a daughter.

H. JAMESON

WEATHER OF FEBRUARY 1958

Northern Hemisphere

The mean pressure chart for the month showed a large low pressure area extending from the east coast of the United States across the North Atlantic between approximately 35° and 65°N., and another extending across northern Europe into north-west Russia. Associated with these low pressure areas were large areas of negative pressure anomaly, the largest anomalies being −13 millibars south of Nova Scotia and −13 millibars near Leningrad. The Azores high was displaced east of its normal position and appeared as a high over the northern Sahara. As a result of this unusual pressure distribution, the belt of surface westerlies across the Atlantic was further south than usual in February

and narrower than usual. The westerlies also extended much further east across Europe and Asia than normal, penetrating as far as the Caspian Sea.

Both the position and intensity of the centre of the Siberian anticyclone were normal for the month, but the ridge extending northward from Siberia across the Arctic and linking with the high pressure region over central North America was stronger than usual, with pressure anomalies of up to +10 millibars in the Arctic. As in January, cyclonic activity was exceptionally intense in the North Pacific, where negative pressure anomalies as large as −15 millibars occurred.

Mean temperatures were generally 2° to 5°C. above normal for the month across central Europe and Asia between 40° and 50°N. as a result of the greater penetration of the westerlies, but north-east of the Caspian temperature anomalies of +7°C. occurred. To the north of this belt, over Scandinavia and northern Russia where the westerly or south-westerly flow was weaker than normal, mean temperatures were below the February normal.

The absence of the usual strong advection of cold air from the north-west resulted in mean temperatures up to 8°C. above normal in Labrador and north-east Canada. Smaller positive temperature anomalies were reported from western America but over central and south-eastern states of the United States temperatures were below normal, anomalies of −5°C. occurring in Florida.

The month gave above normal precipitation over central Europe and central Asia, with amounts up to four times the normal at a few stations, but elsewhere over Europe and the Mediterranean the month was drier than usual. Over the north-eastern states of America, where severe blizzards and deep snowdrifts were reported, the total precipitation was about twice the normal for February.

WEATHER OF MARCH 1958

Great Britain and Northern Ireland

The two most striking features of the very cold month of March were the persistent northerly winds from the 5th to the 11th and the equally persistent and cold south-easterly airstream which lasted from the 14th to the 24th.

With an anticyclone in the neighbourhood of south-west England, the opening days of the month were rather mild and mostly dry with a good deal of fog which, however, cleared from most places by midday. There were sunny periods, especially on the 3rd, and temperatures reached the upper fifties in places on the 4th and 5th. Fresh northerly winds reaching gale force locally in Scotland spread, with snow showers, southward across Scotland and northern England on the 5th and to the remainder of the British Isles the following day, bringing a general fall of temperature of about 10°F. There were sunny periods in most districts although moderate falls of snow occurred over parts of north-east England on the 8th, 9th and 10th. Temperature fell progressively and, on the 9th, was below freezing point throughout the day in many northern districts, and at the level of the average night minima for March. Widespread and locally severe frost occurred over the northern part of the country during the next five or six nights; early on the 12th air temperature fell to 2°F. at Aberdeen. A depression, which formed in the Denmark Strait on the 10th, moved across Northern Ireland and northern England late on the 12th and early on the 13th, giving some continuous snow which later turned to rain. There was a marked rise in pressure behind the depression over the North Sea

and this proved to be the beginning of a high pressure area off Scandinavia which maintained a spell of south-easterly winds over most of the country with temperatures about 10°F. below the average, until the 24th. On the 14th air temperature at Aberdeen fell to 0°F. the lowest ever recorded there during March. For ten days a frontal belt lay north-east to south-west over or near south-west England giving prolonged periods of rain in its neighbourhood, but elsewhere weather was cold, fairly sunny and dry apart from snow showers which, however, were mainly slight. On the 24th milder air, which had been off south-west England for the previous ten days, began to move north-east across the British Isles. In the warmer airstream, weather was cloudy with rain at times; thunderstorms developed over south-east England on the 30th. On the 28th and 29th a depression moved north along the west coast of Great Britain and a slow moving associated front gave heavy rainfall in parts of north-east England and east Scotland. Temperature did not rise much above 40°F. in north-east Scotland, but in southern England 60°F. was reached in London on the 27th, at Mildenhall on the 28th and at Ross on Wye on the 30th.

Mean temperature for the month ranged from about 3°F. below average over Cornwall to more than 6°F. below average in the Aberdeen area; during the second and third weeks of the month temperatures were 8–10°F. below normal over much of the country. At Aberdeen temperature fell to freezing point or below on seventeen nights and was at this level continuously from the evening of the 7th until the afternoon of the 11th. Rainfall, expressed as a percentage of the 1916–50 average, was 86, 82 and 69 per cent over England and Wales, Scotland and Northern Ireland respectively. It was less than half the average over much of north-west England and south-west Scotland and was more than twice the average along the Northumberland coast and along the east coast of Scotland from St. Andrews to Peterhead. More than three times the average occurred in a small area around Montrose, Angus. Sunshine was near the average over much of the British Isles, but it was particularly dull over Cornwall and the Channel Islands.

The cold winds and night frosts during most of the month retarded the growth of, and did some damage to, spring crops including rhubarb, lettuce, spring greens and winter cauliflowers. Fuel used in heated glasshouses was correspondingly increased. Ground conditions, often frozen and snow covered and later very wet, continued to hold up much outside work, but towards the end of the month some districts reported the work, including potato planting, was progressing satisfactorily.

WEATHER OF APRIL 1958

The general character of the weather is shown by the following provisional figures :—

	AIR TEMPERATURE			RAINFALL		SUNSHINE
	Highest	Lowest	Difference from average daily mean†	Percentage of average*	No. of days difference from average*	Percentage of average†
	°F.	°F.	°F.	%		%
England and Wales ...	75	15	−1·6	51	−5	100
Scotland	68	15	−0·3	75	−2	100
Northern Ireland ...	66	24	−0·3	63	−2	95

*1916–1950 †1921–1950

RAINFALL OF APRIL 1958

Great Britain and Northern Ireland

County	Station	In.	*Per cent of Av.	County	Station	In.	*Per cent of Av.
London	Camden Square	1·74	88	*Carm.*	Pontcrynfe	1·26	37
Kent	Dover	1·82	90	*Pemb.*	Maenclochog, Dolwen Br.	1·55	42
"	Edenbridge, Falconhurst	1·29	56	*Radnor*	Llandrindod Wells	·94	36
Sussex	Compton, Compton Ho.	·82	33	*Mont.*	Lake Vyrnwy	2·19	54
"	Worthing, Beach Ho. Pk.	·77	43	*Mer.*	Blaenau Festiniog	4·84	75
Hants	St. Catherine's L'thouse	·55	28	"	Aberdovey	1·43	58
"	Southampton, East Pk.	·59	27	*Carn.*	Llandudno	·85	50
"	South Farnborough	·98	49	*Angl.*	Llanerchymedd	1·13	50
Herts.	Harpenden, Rothamsted	1·23	59	*I. Man*	Douglas, Borough Cem.	1·11	42
Bucks.	Slough, Upton	1·19	62	*Wigtown*	Newtown Stewart	1·35	59
Oxford	Oxford, Radcliffe	1·08	57	*Dumf.*	Dumfries, Crichton R.I.	·95	39
N'hants.	Wellingboro' Swanspool	·79	42	"	Eskdalemuir Obsy.	2·49	6[illegible]
Essex	Southend W.W.	1·41	86	*Roxb.*	Crailing	2·23	14[illegible]
Suffolk	Ipswich, Belstead Hall	·89	50	*Peebles*	Stobo Castle	1·49	61
"	Lowestoft Sec. School	1·13	68	*Berwick*	Marchmont House	2·33	12[illegible]
"	Bury St. Ed., Westley H.	1·30	61	*E. Loth.*	N. Berwick	2·09	14[illegible]
Norfolk	Sandringham Ho. Gdns.	1·08	52	*Midl'n.*	Edinburgh, Blackf'd H.	1·38	8[illegible]
Dorset	Creech Grange	·61	27	*Lanark*	Hamilton W.W., T'nhill	1·16	5[illegible]
"	Beaminster, East St.	·97	39	*Ayr*	Prestwick	1·16	61
Devon	Teignmouth, Den Gdns.	·58	27	"	Glen Afton, Ayr. San	1·98	58
"	Ilfracombe	1·03	45	*Renfrew*	Greenock, Prospect Hill	2·35	66
"	Princetown	2·29	44	*Bute*	Rothesay, Ardencraig	0·00	00
Cornwall	Bude	·98	51	*Argyll*	Morven, Drimnin	2·83	77
"	Penzance	1·63	65	"	Poltalloch	2·54	76
"	St. Austell	1·24	42	"	Inveraray Castle	4·11	80
"	Scilly, St. Mary	1·22	58	"	Islay, Eallabus	1·59	52
Somerset	Bath	1·07	51	"	Tiree	2·10	81
"	Taunton	·55	28	*Kinross*	Lock Leven Sluice	1·74	81
Glos.	Cirencester	·83	36	*Fife*	Leuchars Airfield	1·73	113
Salop	Church Stretton	·47	18	*Perth*	Loch Dhu	3·10	63
"	Shrewsbury, Monkmore	·51	28	"	Crieff, Strathearn Hyd.	1·20	53
Worcs.	Worcester, Diglis Lock	·43	23	"	Pitlochry, Fincastle	·82	43
Warwick	Birmingham, Edgbaston	·73	32	*Angus*	Montrose Hospital	1·70	92
Leics.	Thornton Reservoir	·78	36	*Aberd.*	Braemar	1·27	56
Lincs.	Cranwell Airfield	·46	28	"	Dyce, Craibstone	1·67	76
"	Skegness, Marine Gdns.	·90	56	"	New Deer School House	1·49	67
Notts.	Mansfield, Carr Bank	0·00	00	*Moray*	Gordon Castle	1·42	78
Derby	Buxton, Terrace Slopes	2·22	66	*Inverness*	Loch Ness, Garthbeg	2·35	85
Ches.	Bidston Observatory	·49	29	"	Fort William	4·78	100
"	Manchester, Airport	·76	40	"	Skye, Duntulm	2·54	75
Lancs.	Stonyhurst College	1·83	68	"	Benbecula	2·09	82
"	Squires Gate	1·20	65	R. & C.	Fearn, Geanies	1·16	79
Yorks.	Wakefield, Clarence Pk.	·42	23	"	Inverbroom, Glackour	4·03	95
"	Hull, Pearson Park	1·29	70	"	Loch Duich, Ratagan	5·76	107
"	Felixkirk, Mt. St. John	1·05	57	"	Achnashellach	5·48	98
"	York Museum	·61	36	*Suth.*	Stornoway	1·76	76
"	Scarborough	1·19	67	*Caith.*	Lairg, Crask	2·68	69
"	Middlesbrough	1·48	98	"	Wick Airfield	1·48	73
"	Baldersdale, Hury Res.	1·45	58	*Shetland*	Lerwick Observatory	1·63	60
Nor'l'd	Newcastle, Leazes Pk.	1·23	70	*Ferm.*	Belleek	2·29	80
"	Bellingham, High Green	2·16	100	*Armagh*	Armagh Observatory	1·20	58
"	Lilburn Tower Gdns	2·86	147	*Down*	Seaforde	1·61	64
Cumb.	Geltsdale	2·17	94	*Antrim*	Aldergrove Airfield	1·25	57
"	Keswick, High Hill	1·70	52	"	Ballymena, Harryville	1·70	62
"	Ravenglass, The Grove	1·45	59	*L'derry*	Garvagh, Moneydig	2·16	81
Mon.	A'gavenney, Plâs Derwen	·61	21	"	Londonderry, Creggan	2·17	72
Glam.	Cardiff, Penylan	·74	29	*Tyrone*	Omagh, Edenfel	1·67	64

* 1916–1950

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